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Model studies on circular footing supported on geocell reinforced sand underlain by soft clay

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Abstract

The effectiveness of geocell reinforcement placed in the granular fill overlying soft clay beds has been studied by small-scale model tests in the laboratory. The test beds were subjected to monotonic loading by a rigid circular footing. Footing load, footing settlement and deformations on the fill surface were measured during the tests. The influence of width and height of geocell mattress as well as that of a planar geogrid layer at the base of the geocell mattress on the overall performance of the system has been systematically studied through a series of tests. The test results indicate that with the provision of geocell reinforcement in the overlying sand layer, a substantial performance improvement can be obtained in terms of increase in the load carrying capacity and reduction in surface heaving of the foundation bed. An additional layer of geogrid placed at the base of the geocell mattress further enhances the load carrying capacity and stiffness of the foundation bed. Its beneficial effect decreases with the increase in the height of the geocell mattress. A seven-fold increase in the bearing capacity of the circular footing can be obtained by providing geocell reinforcement along with a basal geogrid layer in the sand bed underlying soft clay.

Keywords: Model studies; Reinforced sand; Clay; Geocell reinforcement; Circular footing

1. Introduction

The bearing capacity of footings on soft clay can be improved considerably by placing a layer of compact granular fill of limited thickness with geotextile or geogrid reinforcement at sand clay interface (Jarrett, 1980; Giroud and Noiray, 1981; Love

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Nomenclature

b	width of geocell layer
D	diameter of the footing
d	diameter of an equivalent circular area of geocell pocket opening
δ	surface deformation
H	thickness of the overlying sand layer
h	height of geocell layer
Δh	vertical spacing between successive geogrid layers
I_f	bearing capacity improvement factor for geocell or layers of planar geogrid
I_{fg}	bearing capacity improvement factor for geocell with basal geogrid
N	number of planar geogrid layers
q_0	footing pressure on unreinforced foundation bed
q_c	footing pressure with geocell or layers of planar geogrid reinforcement
q_{cg}	footing pressure with geocell and basal geogrid
q_{ult}	ultimate footing pressure on unreinforced foundation bed
s	footing settlement
u	depth to the top of reinforced zone from the base of the footing

et al., 1987; Kim and Cho, 1988; Khing et al., 1994). In this technique the beneficial effects of the reinforcement is derived through membrane action that requires high allowable rut depth.

The geocell reinforcement is a recently developed technique, which is a three-dimensional, polymeric, honeycomb-like structure of cells interconnected at joints. The reinforcing mechanism in the geocells is by all-round confinement of soil within its pockets that completely arrests the lateral spreading of soil. Consequently, a better composite material is formed and the geocell layer behaves as a stiffer mattress that redistributes the footing load over a wider area. Several investigations have been reported highlighting the beneficial use of geocell reinforcement in the construction of foundations and embankments. Rea and Mitchell (1978) and Mitchell et al. (1979) identified different modes of failure of geocell by conducting a series of model tests on footings supported over sand beds reinforced with square-shaped paper grid cells. Shimizu and Inui (1990) carried out load tests on hexagonal-shaped single geotextile cell filled with sand overlying soft soil. Cowland and Wong (1993) reported a case study of the performance of a geocell mattress supported embankment on soft clay. Jenner et al. (1988) making use of slip line theory have proposed a methodology to calculate the increase in bearing capacity due to the provision of geocell mattress at the base of the embankment resting on soft soil. Krishnaswamy et al. (2000) carried out a series of laboratory model tests on geocell mattress supported earth embankments constructed over soft clay bed. Dash et al. (2001a, b) investigated the reinforcing efficacy of the geocell mattress within a homogeneous sand bed supporting a strip footing.

The work reported in this paper consists of results from laboratory model tests on circular footing supported by dense sand layer underlain by soft clay bed with and without geocell reinforcement in the sand layer. The primary objective of this study is to evaluate the influence of different parameters, on the overall performance improvement of the footing due to the provision of geocell reinforcement, the details of which are presented in a later section.

2. Materials used in the experiments

A natural silty clay soil was used for this study which had 60% fines fraction smaller than 75-μm sieve size. Fig. 1 depicts the particle size distribution of this soil. The liquid limit, plastic limit and specific gravity of the soil were found to be 40%, 17% and 2.66, respectively. As per the Unified Soil Classification System (USCS) the soil can be classified as clay with low plasticity (CL). This soil was used in extremely soft condition due to which it was not possible to prepare samples out of it for standard triaxial compression test. However, the shear strength of the same was obtained through vane shear test which has been reported in a later section.

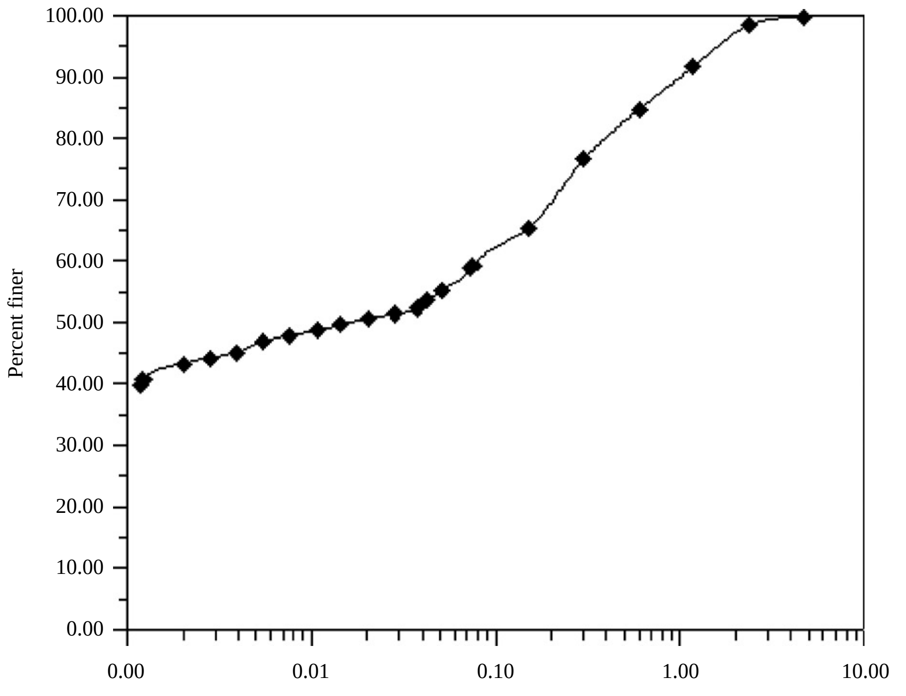

Fig. 1. Particle size distribution of the clay used in the study.

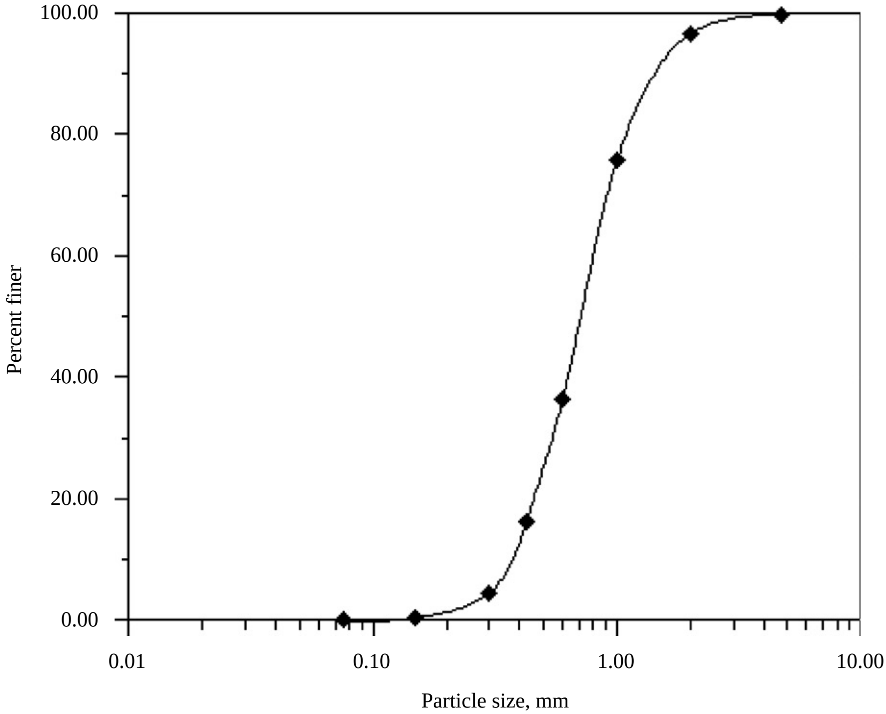

Fig. 2. Particle size distribution of the sand used in the study.

The sand used in this investigation was a dry sand, whose particle size distribution is shown in Fig. 2. It has a coefficient of uniformity (C_u) of 2.22, coefficient of curvature (C_c) of 1.05, effective particle size (D_{10}) of 0.36 mm, and specific gravity of 2.63. The soil is classified as poorly graded sand with letter symbol SP according to the USCS. In all tests the average unit weight and relative density (ID) of sand was kept at 16.8 kN/m^3 and 70%, respectively. The friction angle of the dry sand at 70% relative density as determined from standard triaxial compression tests is found to be 41°. Typical axial strain—deviatoric stress curves of the dry sand as obtained from triaxial compression tests are shown in Fig. 3.

The geocell layers were formed using a biaxial geogrid. The properties of the geogrid are given in Table 1.

3. Laboratory model tests

3.1. Set-up

The model tests were conducted in a test bed-cum-loading frame assembly in the laboratory. The soil beds were prepared in a test tank with inside dimensions of 900 mm length × 900 mm width × 600 mm height. The model footing used was made

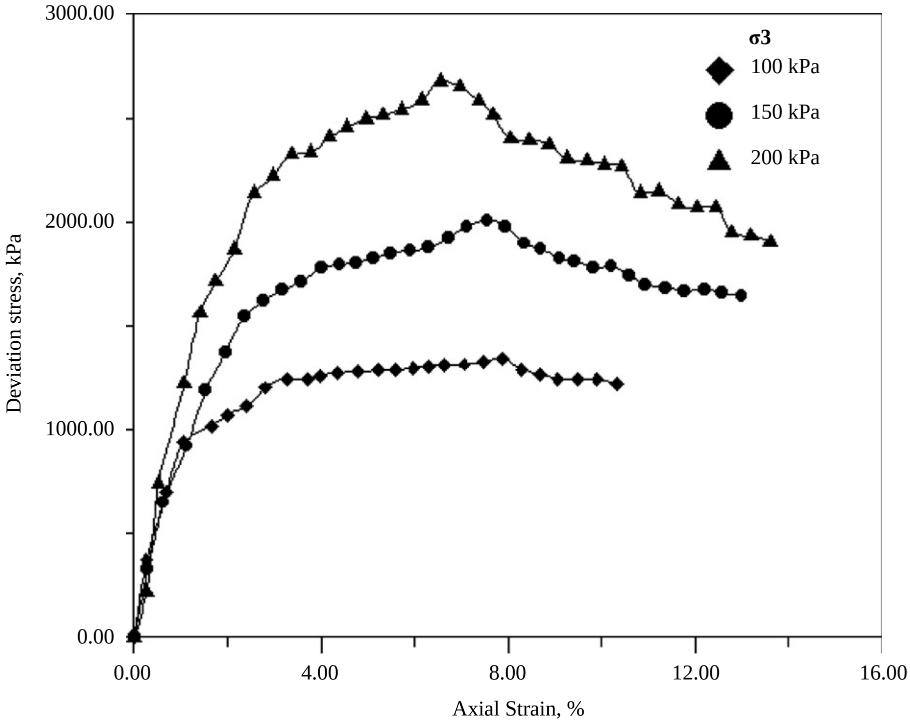

Fig. 3. Stress–strain curves for sand with different confining pressures obtained from triaxial compression tests.

Table 1
Properties of the geogrid

Parameter	Quantity
Polymer	Polypropylene
Aperture size (MD $\times$ XMD)	41 mm $\times$ 31 mm
Peak tensile strength (MD $\times$ XMD)	14.5 kN/m $\times$ 20.5 kN/m
Yield point strain (MD $\times$ XMD)	16% $\times$ 13%

MD: machine direction, XMD: cross-machine direction.

of a rigid steel plate and measured 150 mm diameter (D) and 30 mm thickness. The base of the model footing was made rough by cementing a thin layer of sand to it with epoxy glue. The footing was loaded with a hydraulic jack supported against the reaction frame. In pilot tests the pressures on the walls of the test tank were measured using earth pressure cells. No pressure was recorded till the end of the tests. This indicates that the tank used in the present investigation is large enough and is not likely to interfere with the failure zones and hence the experimental results.

3.2. Preparation of clay beds

The clayey soil was first pulverised and then mixed with predetermined amount of water. In order to allow uniform moisture distribution the moist soil was kept in airtight containers for about a week. To prepare the test bed, the moist soil was placed in the test box and compacted in 25-mm thick layers till the desired height was reached. For each layer the required amount of soil to produce a desired bulk density was weighted out and placed in the test box making use of a metal scoop. The soil was then gently levelled out and compacted to proper depth by placing a wooden board on the surface and hitting the board with a drop hammer, using depth marking on the sides of the box as guide. Through a series of trials the amount of soil, water content of soil, height of fall and number of blows of the drop hammer required to achieve the desired density for each lift were determined a priori. By carefully controlling the water content and compaction, a fairly uniform test condition was achieved throughout the test programme. Each layer was compacted uniformly so as to achieve a uniform density in all the test beds. In order to verify the uniformity of the test bed undisturbed samples were collected from different locations in the test bed to determine the in situ unit weight, moisture content and vane shear strength of the clay soil. The values of these parameters of the compacted soil at different locations of the test tank were found to be almost the same. Table 2 presents the average properties of the compacted moist clay during the tests.

3.3. Preparation of reinforced sand beds

The geocell mattress was formed on top of the compacted clay bed. The geocell layer was prepared by cutting the geogrids to required length and height from full rolls and placing them in transverse and diagonal directions with bodkin joints (plastic strips) inserted at the connections (Bush et al., 1990). All the geocell layers in the present investigation were prepared in chevron pattern only, as it gives better performance improvement in comparison to the diamond pattern (Dash et al., 2001a). After formation of geocell layer the geocell pockets were filled with sand using sand raining technique. The height of fall to achieve the desired relative density was determined a priori by performing a series of trials with different heights of fall. The relative densities achieved were monitored by collecting samples in small aluminium cans of known volume placed at different locations in the test tank. The difference in densities measured at various locations was found to be less than 1%.

Table 2
Properties of clay bed

Parameter	Quantity
Moisture content	28%
Degree of saturation	100%
Unit weight	$19.5\,kN/m^3$
Vane shear strength	$3.13\,kN/m^2$

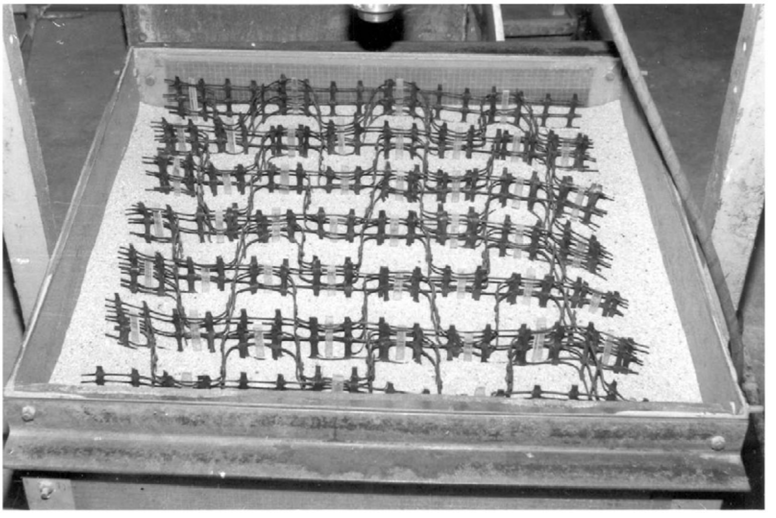

Fig. 4. Photographic view of a typical geocell layer in sand bed.

The density of the soil placed within the geocell mattress was also monitored by collecting soil samples from this layer as explained earlier. The reduction in soil density in this layer due to the presence of geocell mattress was found to be less than 1%, which is negligible. This is because the geocells, being made of geogrids having percent open area of more than 80%, does not affect much the free flow of sand during raining leading to this marginal reduction in placement density. The photographic view of a typical geocell layer in sand bed is shown in Fig. 4.

In the case of planar geogrid reinforcement, at prescribed depth raining of sand was temporarily ceased and the reinforcement was placed on the surface of the sand. After this sand raining was continued.

3.4. Test procedure

Upon filling the tank up to the desired height, the fill surface was levelled and the footing was placed on a predetermined alignment such that the loads from the loading jack would be transferred concentrically to the footing. A recess was made into the footing plate at its centre to accommodate a ball bearing through which vertical loads were applied to the footing. The footing was pushed into the soil at a rate of nearly 2 mm/min. The load transferred to the footing was measured through a pre-calibrated proving ring placed between the ball bearing and the loading jack. Footing settlements were measured through two dial gauges (Dg_2 and Dg_3 see Fig. 5) placed on either side of the centre line of the footing. The deformations (heave/settlement), of the soil surface on either side of the footing were also measured by dial gauges, placed on diametrically opposite sides at a distance of $1.5D$ from the centre of the footing (Dg_1 and Dg_4; see Fig. 5). Small plates of size 20 mm length $\times$ 20 mm width $\times$ 4 mm thickness made of perspex sheet were placed on the

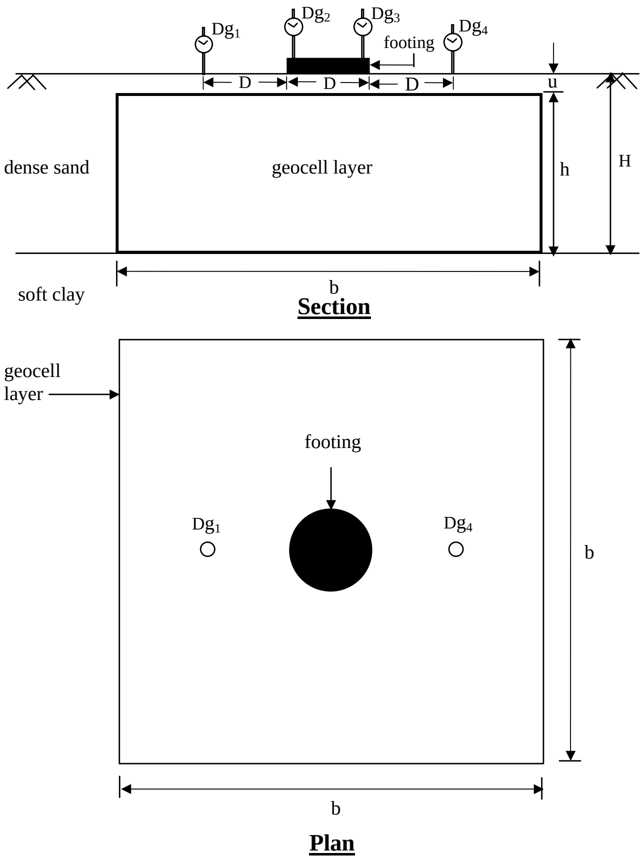

Fig. 5. Definition sketch of geocell reinforced foundation bed.

soil surface at required locations where surface deformations are to be measured. At the centre of the top surface of these plates a small recess was made in which the dial gauge spindle rested. The movement of these surface plates recorded through the dial gauges is taken as the deformation of the soil surface. The footing settlement and the surface deformation data reported here are the average values of the readings taken at the two different points.

3.5. Test variables

The definition sketch of the problem investigated are shown in Figs. 5 and 6. The geocell layers in all the tests were formed in square shape. The pocket size (d) of the geocells is taken as the diameter of an equivalent circular area of the geocell pocket opening. Five different series of tests (i.e. A–E) were carried out by varying different parameters such as width of geocell layer (b) and height of geocell layer (h), the

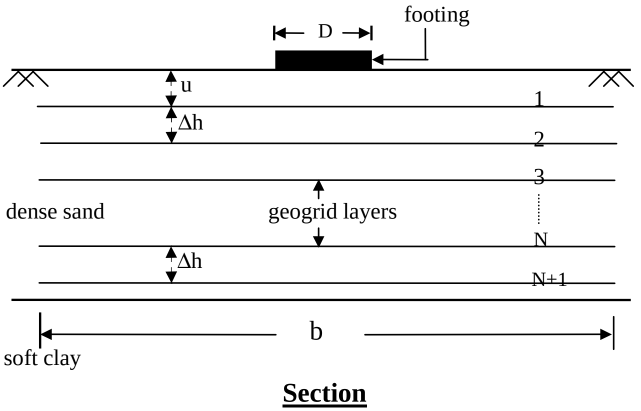

Fig. 6. Definition sketch of planar geogrid reinforced foundation bed.

Table 3
Details of laboratory model tests

Test series	Type of reinforcement	Details of test parameters
A	Unreinforced	Variable parameter: $H/D = 0, 0.52, 0.94, 1.36, 1.78, 2.20, 2.62$ Constant parameter: $C_u = 3.13\,\text{kN/m}^2$, $ID = 70\%$
B	Geocell alone	Variable parameter: $b/D = 1.2, 1.7, 2.2, 3.6, 5.0, 5.6$ Constant parameter: $d/D = 0.8$, $h/D = 1.26$, $u/D = 0.1$
C	Geocell alone	Variable parameter: $h/D = 0.42, 0.84, 1.26, 1.68, 2.10, 2.52$ Constant parameter: $d/D = 0.8$, $b/D = 5.0$, $u/D = 0.1$
D	Geogrid layer below geocell mattress	Variable parameter: $h/D = 0.42, 0.84, 1.26, 1.68, 2.10$ Constant parameter: $d/D = 0.8$, $b/D = 5.0$, $u/D = 0.1$
E	Planar reinforcement layers	$N = 6$, $b/D = 6$, $\Delta u = \Delta h = 0.333D$

details of which are given in Table 3.The pocket size of the geocells (d) was kept constant in all the tests.

Under series A, tests were conducted on unreinforced soil beds with different thickness (H) of the overlying sand layer. In order to have a direct comparison of the results for the unreinforced and reinforced cases, the thickness of the overlying sand layers in this test series was kept equal to the height of the geocell mattresses as tested in other test series.

Test series B and C were conducted with geocell alone. The objective of these two series of tests (i.e. B and C) is to find out the influence of the width and height of the geocell layer on the overall performance of the footing respectively.

Tests in series D were carried out with geocell reinforcement along with planar geogrid layer at its base in order to understand the influence of the additional basal geogrid layer on the behaviour of the system. The planar reinforcement was left free in the soil without being connected to the geocell layer. As per the findings of Dash et al. (2001a) in all the tests the top of the geocell layer was kept at a depth (u) of 0.1 times the footing diameter (i.e. 15 mm) in order to get maximum performance improvement.

Test series E was conducted with layers of planar geogrid in the sand layer overlying soft clay. The objective of this test series is to draw a comparison between the performance of geocell reinforcement system and planar reinforcement system, keeping the thickness of the overlying sand layer and the quantity of reinforcing material in both cases equal. The geocell layer that gives maximum performance improvement has been chosen here for this comparison purpose. In view of this the quantity of geogrid in the planar reinforcement system was kept the same as the quantity of geogrid required for making up the geocell layer that gives maximum performance improvement. As will be discussed in a later section the geocell layer with pocket size (d) of $0.8D$, width (b) of $5D$, and height (h) of $2.1D$ is found to be the one that gives maximum performance improvement. Under the present test conditions the quantity of geogrid required for this configuration is found to be around $4.83\,\mathrm{m}^2$. Khing et al. (1994) have shown that the optimum width of geogrid layer required to mobilise the maximum possible bearing capacity for a given sand–geogrid–clay combination is about six times the width of the footing. Hence in the present investigation the size of the planar geogrid layers was kept as $6D \times 6D$. The number of geogrid layers (N) of size $6D \times 6D$ (i.e. $900\,\mathrm{mm} \times 900\,\mathrm{mm}$) corresponding to $4.83\,\mathrm{m}^2$ quantity is around 6. The same has been adopted in this case. In the present study depth to top reinforcement layer from the base of the footing (u) and vertical spacing between the successive layers (Δh) was kept at $0.333D$ in order to have a uniform distribution of reinforcement throughout the sand bed. The thickness of sand bed in this case was $2.2D$. It should be mentioned here that the value of u and Δh used in the present investigation are similar to that adopted by Omar et al. (1993) in their study on geogrid reinforced foundation beds.

4. Results and discussion

The pressure settlement responses observed from different series of tests are presented in Figs. 7, 8, 10, 12 and 14. The performance improvement due to the provision of geocell reinforcement (Test series B and C) or layers of planar reinforcement (Test series E) is represented using a non-dimensional improvement factor (I_f) which is defined as the ratio of footing pressure (q_c) with geocell or layers of planar reinforcement at a given settlement to the corresponding pressure on unreinforced soil (q_0) at the same settlement. If the footing on unreinforced soil has reached its ultimate capacity at a certain settlement, the bearing pressure (q_0) is taken as the ultimate value (q_{ult}) while calculating I_f at higher settlements. It should be mentioned here that this improvement factor (I_f) is similar to the

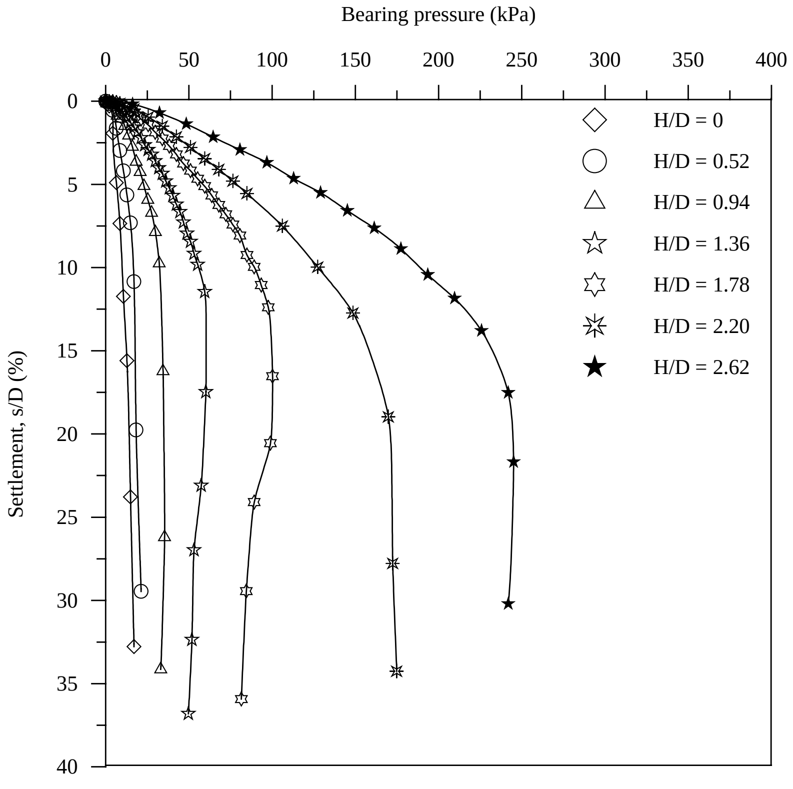

Fig. 7. Variation of bearing pressure with footing settlement for unreinforced foundation beds with different thickness of overlying sand layer—test series A.

bearing capacity ratio (BCR) used by Binquet and Lee (1975) to quantify the bearing capacity improvement due to planar reinforcement in foundation beds under strip loading.

The performance improvement due to the basal geogrid layer (Test series D) is quantified in terms of improvement factor (I_{fg}) which is defined as q_{cg}/q_c in which q_{cg} is the footing pressure with additional geogrid layer with the geocell mattress and q_c is the footing pressure with geocell mattress alone, both at the same footing settlement.

The variation of bearing capacity improvement factors, I_f and I_{fg}, with footing settlement for different cases are shown in Tables 4 and 5, respectively. The footing settlement "s" and surface deformation (settlement/heave) "δ" are also expressed in non-dimensional form in terms of the footing diameter (D) as s/D (%) and δ/D (%). Figs. 9, 11, 13 and 15 depict the pattern of surface deformation variation with footing settlement for different cases where downward deformation (+) is considered as settlement and upward deformation (−) is considered as heave.

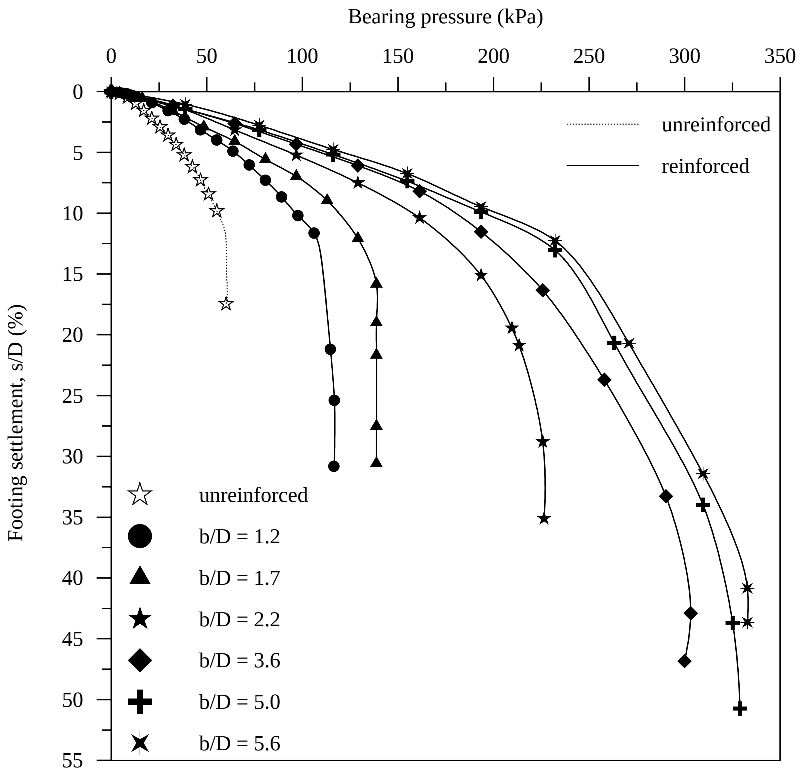

Fig. 8. Variation of bearing pressure with footing settlement for different widths of geocell mattress—test series B.

4.1. General

From the results presented in Tables 4 and 5, it is of interest to note that with the provision of geocell reinforcement (Test series C, $h/D = 1.68$) the load carrying capacity of the footing can be increased as high as six times that of the unreinforced case ($I_f = 6.06$). With the provision of an additional layer of planar reinforcement at the base of the geocell mattress the same could further be enhanced by a factor of about 1.17 ($I_{fg} = 1.17$) thus bringing forth a total improvement of about 7.2 times that of the unreinforced case. At a settlement of around 15–20% of footing diameter, the slope of the pressure settlement responses, are found to reduce slightly. However, this change in slope did not continue after that and the bearing pressure continued to increase with increase in footing settlement. This is believed to be due to the shearing of the small cushion of sand (i.e. $0.1D = 15\,\text{mm}$ thick) present between the geocell mattress and the footing leading to a reduction in the slope of the pressure settlement response. Once this sand shears, it moves away and the footing directly rests on the geocell mattress that enables to further carry load with a little reduced slope in the pressure settlement response (see Figs. 8, 10 and 12). The surface deformation plots

Table 4
Summary of results in terms of bearing capacity improvement factor (I_f) from Test Series: B, C and E

Test series	Variable parameter	Bearing capacity improvement factor (I_f)							
		(s/D) 1%	(s/D) 3%	(s/D) 5%	(s/D) 10%	(s/D) 15%	(s/D) 20%	(s/D) 30%	(s/D) 40%
B	(b/D)								
	1.2	1.62	1.69	1.75	1.75	1.80	1.87	1.91	—
	1.7	1.77	1.88	2.03	2.12	2.26	2.28	2.28	—
	2.2	2.38	2.42	2.54	2.81	3.17	3.48	3.71	—
	3.6	2.46	2.77	2.98	3.20	3.57	4.00	4.61	4.93
	5.0	2.46	2.88	3.07	3.49	3.98	4.26	4.88	5.26
	5.6	2.92	3.15	3.32	3.63	4.03	4.40	5.00	5.43
C	(h/D)								
	0.42	1.50	2.35	2.50	2.80	3.12	3.43	4.00	4.20
	0.84	2.09	2.57	2.87	3.31	3.82	4.17	4.47	4.73
	1.26	2.15	2.80	3.00	3.49	3.98	4.26	4.88	5.26
	1.68	2.25	2.80	3.00	3.59	4.34	4.95	5.65	6.06
	2.10	2.12	2.35	2.63	3.29	3.88	4.17	4.65	5.26
	2.52	1.71	1.74	2.00	2.53	2.94	3.35	3.84	4.40
E	Planar layers	1.92	2.05	2.21	2.64	3.00	3.32	4.18	4.94

Table 5
Summary of results in terms of bearing capacity improvement factor (I_{fg}) from Test Series: D

Test series	Variable parameter	Bearing capacity improvement factor (I_{fg})							
		(s/D) 1%	(s/D) 3%	(s/D) 5%	(s/D) 10%	(s/D) 15%	(s/D) 20%	(s/D) 30%	(s/D) 40%
D	(h/D)								
	0.42	1.33	1.40	1.40	1.40	1.53	1.69	1.85	2.16
	0.84	1.26	1.30	1.33	1.41	1.46	1.51	1.73	1.96
	1.26	1.21	1.26	1.38	1.38	1.38	1.42	1.45	1.55
	1.68	1.07	1.09	1.13	1.13	1.13	1.12	1.13	1.17
	2.10	1.06	1.06	1.06	1.07	1.07	1.07	1.14	1.14

(Figs. 9, 11 and 13) indicate that the geocell reinforcement substantially reduces the heaving of the fill surface. The test results are further analysed in detail in the following subsections.

4.2. *Effect of width of geocell mattress*

From the results depicted in Fig. 8 and Table 4 (Test series B) it may be seen that even with a geocell mattress of plan area almost equal to that of the footing

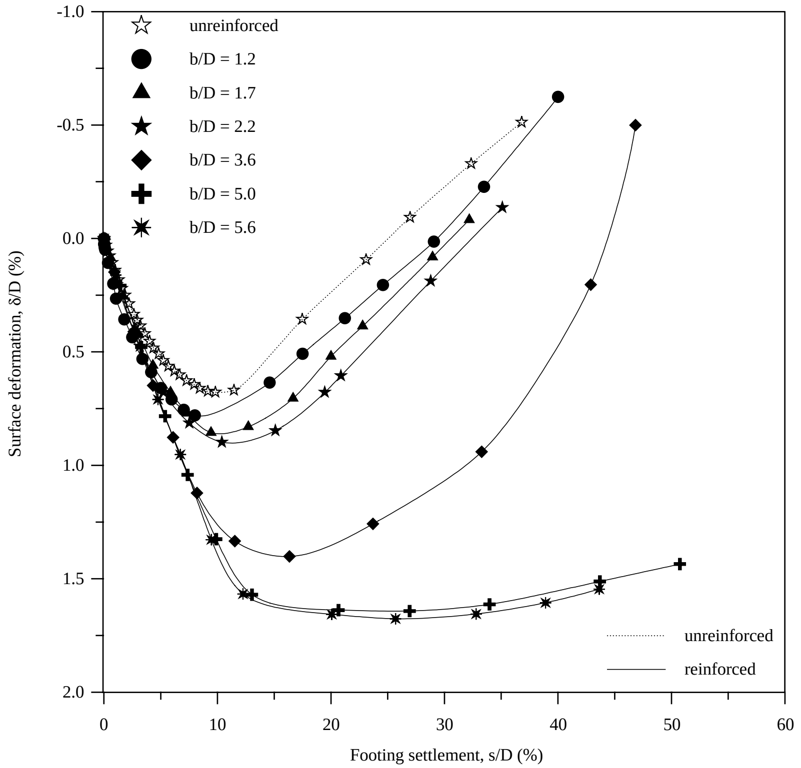

Fig. 9. Variation of surface deformation with footing settlement for different widths of geocell mattress—test series B.

(i.e. $b/D = 1.2$), significant performance improvement is obtained both in terms of load carrying capacity and stiffness (slope of the pressure settlement response) of the soil bed. This is because the encapsulated sand within the geocell pocket owing to the confinement effect from the geocell walls behaves as a relatively rigid member. This rigid member supports the footing load through mobilisation of frictional resistance over its outer periphery throughout the height of the geocell wall that reduces pressure on the underlying soft soil thereby giving rise to an increase in the performance.

The improvement factor is found to increase with the increase in the width of the geocell layer up to a b/D ratio of 5 beyond which it is negligible. This trend can better be explained from the surface deformation plots presented in Fig. 9. The heaving of the fill surface is found to decrease with increase in the width of the geocell layer. For the cases of $b/D \leqslant 3.6$ the fill surface is found to undergo settlement in the initial stages of loading followed by significant heaving at relatively larger footing settlement. However, at higher b/D ratios the fill surface is found to have settled predominantly even at larger footing settlements. This indicates that with the increase in the width of the geocell layer it inhibits the development of rupture planes

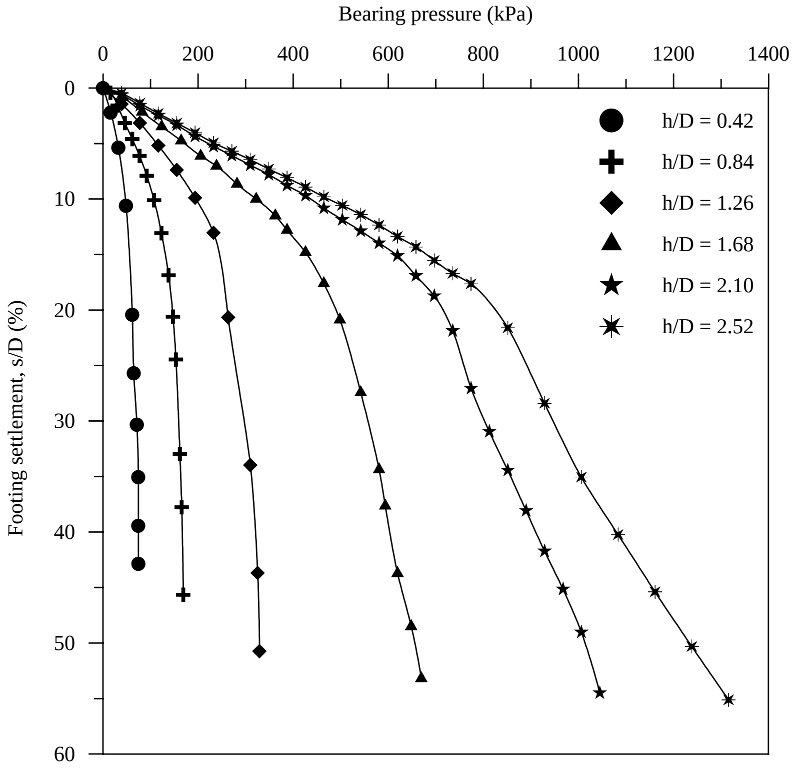

Fig. 10. Variation of bearing pressure with footing settlement for different heights of geocell mattress—test series C.

in the soil bed thereby inducing a better composite behaviour which gives rise to reduction of surface heaving. Beyond a certain width, the geocell layer almost arrests all the potential failure planes thus preventing the soil heave substantially. Besides, the geocell mattress with higher plan area redistributes the footing pressure over a wider area. These two factors have brought about the increase in the load carrying capacity of the footing. After a certain stage further improvement in load carrying capacity with the increase in the width of the geocell mattress is found to be negligible. This is attributed to the local buckling of geocell wall and punching of soil just below the footing.

4.3. Effect of height of geocell mattress

Figs. 10 and 11 show the influence of the height of the geocell layer (h/D) on the overall performance of the footing in terms of load carrying capacity and surface deformation respectively. From Fig. 10 it could be observed that there is substantial increase in the initial stiffness of the pressure settlement response as well as load carrying capacity of the foundation bed with the increase in the height of the geocell

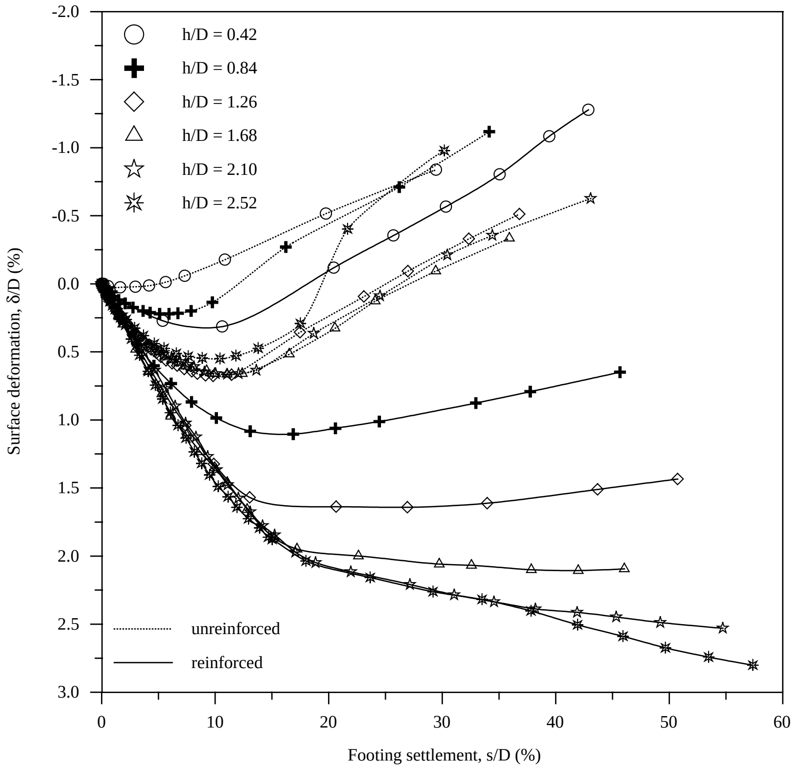

Fig. 11. Variation of surface deformation with footing settlement for different heights of geocell mattress—test series C.

mattress till $h/D = 2.1$ beyond which it is marginal. Fig. 11 indicates that with the increase in the geocell height, the heaving on the fill surface reduces and for higher heights ($h/D \geqslant 2.1$) the fill surface continues to settle even up to footing settlements as high as 55% (i.e. $s/D = 55\%$). Upon loading, the soil within the geocell pocket just below the footing tends to push down into the soft subgrade by overcoming frictional resistance on the geocell wall. With increase in the height of the geocell mattress the overall frictional resistance on the geocell walls increases due to the increase in the surface area which at some stage completely arrests the downward movement of the soil (indicated by the surface deformation changing from heave to settlement). As a result the entire geocell mattress behaves as a composite body thereby giving rise to a better performance improvement. Besides, with the increase in the height of the geocell layer, the moment of inertia and hence bending and shear rigidity of the geocell mattress increases, which redistributes the footing pressure over a wider area and hence increases the performance of the footing. However, beyond a certain height ($h/D = 2.1$), the increased flexural and shear rigidity of the geocell layer remains immobilised because of the local buckling of the geocell walls just under the footing leading to lower performance improvement.

It could be seen from the results presented in Table 4 corresponding to test series C, that the bearing capacity improvement factor (I_f) increases with the increase in the height of the geocell mattress till h/D of 1.68 beyond which it is found to decrease. It should be mentioned here that it is the percentage increase in improvement with respect to the unreinforced case (i.e. I_f) that reduces, not the total load carrying capacity which increases with increase in the geocell height as depicted in Fig. 10. The increase in performance improvement with increase in the height of the geocell mattress is believed to be due to the increase in its overall rigidity as explained earlier. It can be seen from Fig. 7 that in the unreinforced case for higher thickness of sand fill (i.e. $H/D > 1.68$) the proportionate increase in the slope of the pressure-settlement response with increase in sand thickness (H/D) is relatively higher as compared to the cases with lower thickness of sand fill. As the overlying sand layer carries higher load, relatively lower percentage of load is transferred to the geocell reinforcement. As a result of which the strength of the geocell reinforcement remains immobilised thereby giving rise to an apparent reduction in the performance improvement.

4.4. Effect of basal geogrid layer

Fig. 12 presents the variation of bearing pressure with footing settlement for geocell mattress of different heights, with and without a planar reinforcement layer at its base (Test series C and D), where solid and dotted lines represent the case with and without the basal geogrid layer, respectively. It could be observed that the basal geogrid layer further improves the performance of the footing both in terms of load carrying capacity and stiffness of the soil bed. From the results depicted in Table 5 through series D it could be noted that for $h/D = 0.42$ a planar geogrid layer at the base of the geocell mattress could bring a further improvement in bearing capacity of around two times the case with geocell alone ($I_{fg} = 2.16$). The beneficial effect of the basal geogrid layer is found to be higher at larger settlements of the footing. It is postulated that the geogrid layer contributes to the performance improvement by resisting the downward deflection of the geocell mattress under footing load through mobilisation of its strength and membrane action. At higher settlements the geocell layer deflects more thereby inducing higher deformation in the geogrid layer at its base. As a result the geogrid layer gets strained more and hence mobilises higher strength that gives rise to higher performance improvement. Besides there might be some improvement due to separation, which has not, been quantified in this study. Further it is noticed that the influence of the basal geogrid layer reduces with the increase in the height of the geocell mattress and becomes marginal for $h/D \geqslant 1.68$, especially in the lower settlement range (improvement less than 10%). This is because with increase in the height of the geocell mattress its rigidity increases leading to more uniform settlement at the base of the geocell mattress thereby reducing contact pressure on the underlying soil. This in turn mobilises lower strength in the basal geogrid layer leading to its lower contribution to the overall performance improvement.

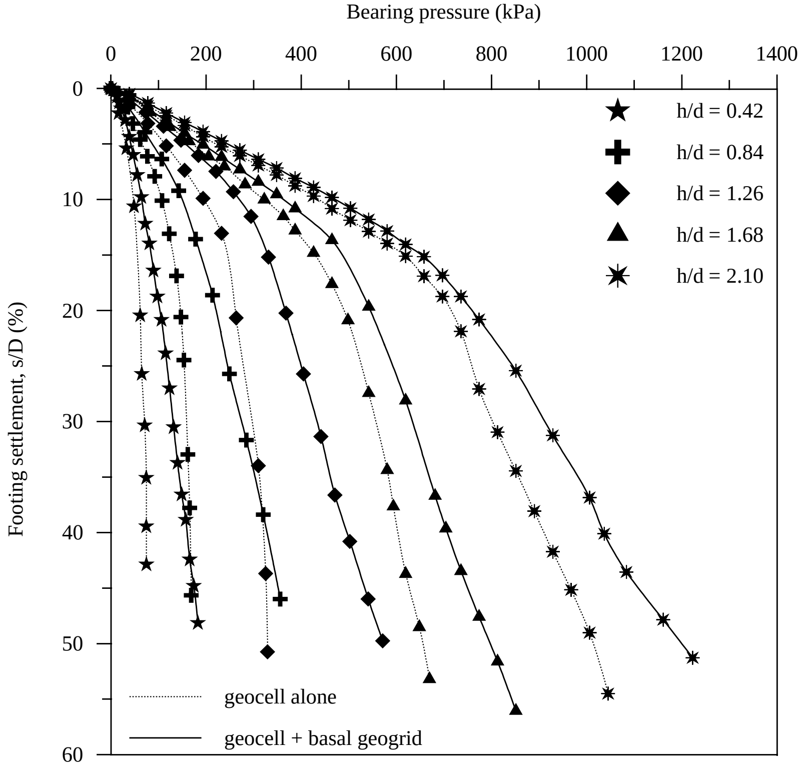

Fig. 12. Variation of bearing pressure with footing settlement for different heights of geocell mattress with and without basal geogrid layer—test series C and D.

Fig. 13 brings out the influence of the basal geogrid layer in terms of the surface deformations measured on the fill surface. It could be seen that the fill surface undergoes lesser settlement with the provision of the basal geogrid layer indicating that the basal geogrid layer arrests the downward deflection of the geocell mattress. The influence of basal geogrid layer in reducing surface settlement is found to be marginal at higher height of geocell mattress. These findings establish the above said argument regarding the bearing capacity improvement due to the provision of the basal geogrid layer. For the case with $h/D = 0.42$ little reduction in surface heave is noticed at relatively larger settlements. In this case the sand bed being of limited thickness the dilation induced surface heave is very small and major part of it is due to the heaving of the clay bed as the tests are carried out at nearly undrained condition. The basal geogrid being just above the clay surface arrests the heaving by virtue of its flexural rigidity mobilised through frictional resistance from the upper sand layer as well as membrane action thereby reducing the overall heaving on the fill surface.

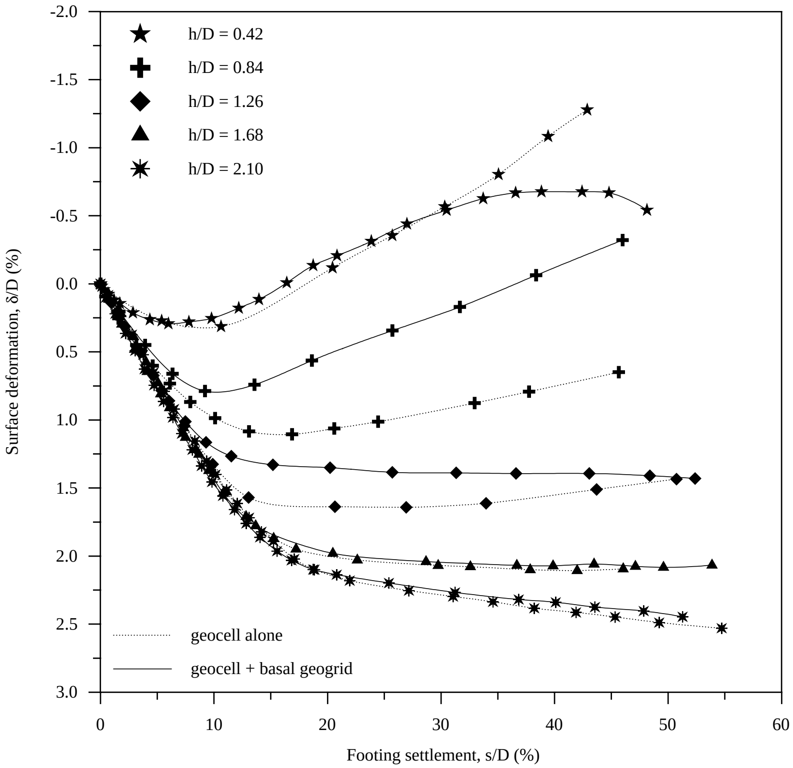

Fig. 13. Variation of surface deformation with footing settlement for different heights of geocell mattress with and without basal geogrid layer—test series C and D.

4.5. Comparison of geocell and planar reinforcement

Figs. 14 and 15 present the comparison of performance of geocell reinforced foundation bed with that reinforced with planar reinforcement layers in terms of pressure settlement behaviour and surface deformation behaviour, respectively. It should be mentioned here that this comparison analysis is made keeping the quantity of geogrid material same in both the cases as explained earlier. From the pressure settlement responses it is seen that the planar reinforcement system has lower stiffness (i.e. slope of the pressure settlement response curve) and lesser load carrying capacity as compared with the geocell reinforced one. The same can also be observed from the comparison of the values of bearing capacity improvement factors presented in Table 4 corresponding to the planar reinforcement case (Test series E) against the values for the geocell layer giving maximum benefit (Test series C with h/D of 2.1). In the case of planar reinforcement system the soil between two successive layers gets squeezed out once it overcomes frictional resistance on the reinforcement surface that inhibits the composite nature of the total system thereby reducing the load carrying capacity. While in the case of geocell reinforcement the

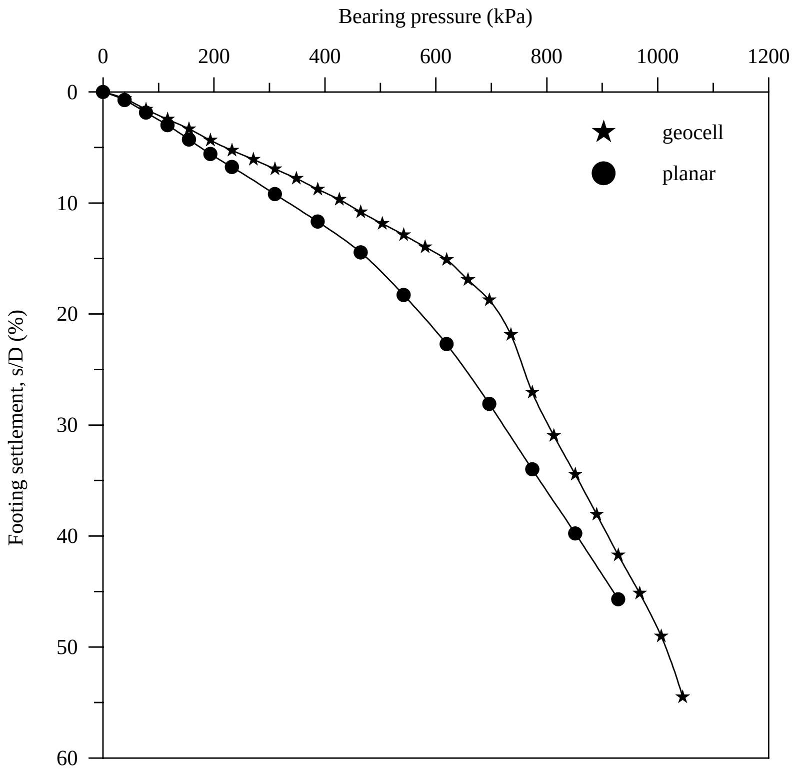

Fig. 14. Variation of bearing pressure with footing settlement for geocell reinforced system and multi-layer planar geogrid reinforced system—Test series C and E.

cells completely encased the soil and provide all-round confinement that makes the geocell mattress to behave as a composite body even at larger footing settlement thereby imparting a higher load carrying capacity to the system. While the fill surface in case of geocell mattress continues to settle even up to the end of the test, the planar reinforced system has predominantly heaved indicating that the soil between the geogrid layers has been sheared off (Fig. 15). This observation clearly establishes the above said argument.

5. Conclusions

This paper has presented the laboratory model test results of load tests on circular footing supported on geocell reinforced sand overlying soft clay beds. These laboratory model test results though have scale effects, provide insight into the basic reinforcing mechanism that establishes the load deformation behaviour of the footing supported on geocell mattress underlying soft clay bed. Large scale tests carried out by Milligan et al. (1986) indicate that the general mechanisms and

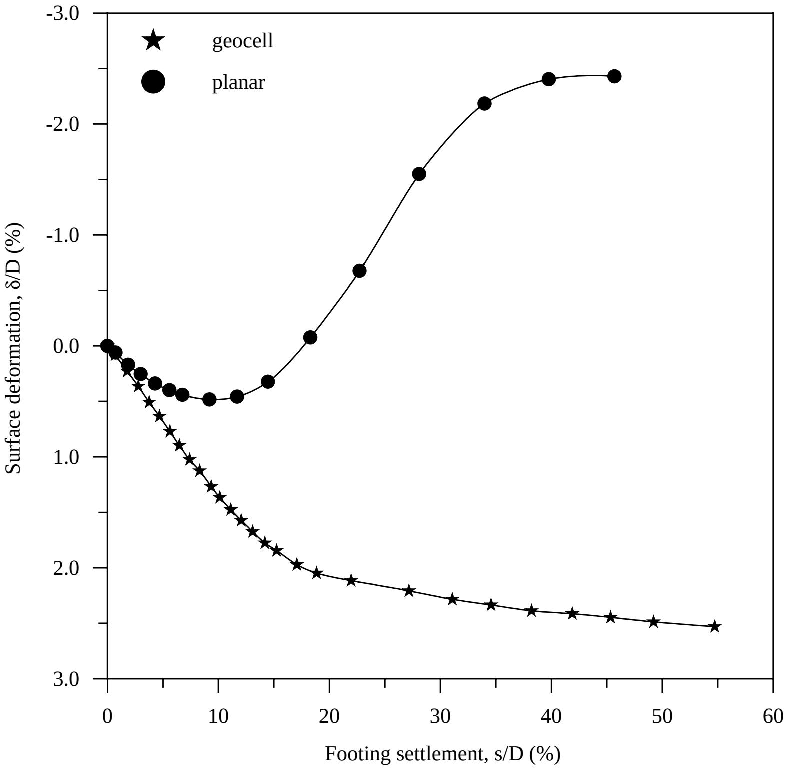

Fig. 15. Variation of surface deformation with footing settlement for geocell reinforced system and multi-layer planar geogrid reinforced system—Test series C and E.

behaviour observed in the model tests are reproduced at large scale. Consequently, the findings from the present study will provide general guidelines for construction as well as large-scale field tests and would lead to the developments of a rational design methodology. However, the extrapolation of the results from these model tests to field cases can be done making use of a suitable scaling law with careful consideration of different parameters as discussed by Butterfield (1999) and Fakher and Jones (1996).

Based on the findings from the present investigation the following conclusions can be made on the behaviour of circular footings resting on geocell reinforced sand beds underlain by soft clay.

1. Provision of geocell reinforcement in the overlying sand layer improves the load carrying capacity and reduces the surface heaving of the foundation bed substantially.
2. The performance improvement increases with increase in the width of the geocell layer up to b/D of 5 beyond which it is negligible. Good improvement in the load carrying capacity of the foundation bed can be obtained even with geocell mattress of width almost equal to the diameter of the footing ($b/D = 1.2$).

3. The overall performance improvement is significant up to a geocell height of about two times the diameter of the footing ($h/D = 2.1$). Beyond that height, the improvement is only marginal.
4. An additional layer of planar geogrid at the base of the geocell mattress further enhances the performance improvement both in terms of load carrying capacity and stiffness of the foundation bed. The beneficial effects of the basal geogrid layer decreases with increase in the height of geocell mattress and become marginal at larger heights ($h/D \geqslant 1.68$).
5. A seven-fold increase in the bearing capacity of the footing can be obtained by providing geocell reinforcement of adequate dimensions along with a layer of planar geogrid at its base in the sand layer overlying the soft clay bed.
6. From the results obtained through limited tests carried out under the present investigation it appears that for same quantity of geogrid material, geocell reinforcement system yields better performance improvement than planar reinforcement system.

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